PERGAMON

Geodynamics 27 (1999) 277–288

JOURNAL OF GEODYNAMICS

Geologic processes of accretion in the Cascadia subduction zone west of Washington State

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Received 1 November 1997; received in revised form 18 December 1997; accepted 19 December 1997

Abstract

The continental margin west of Oregon and Washington undergoes a northward transition in morphology, from a relatively narrow, steep slope west of Oregon to a broad, midslope terrace off Washington. Multichannel seismic (MCS) reflection data collected over the accretionary complex show that the morphologic transition is accompanied by significant change in accretionary style: West of Oregon the direction of thrust vergence in the wedge toe flip-flops between landward and seaward, whereas off Washington, thrust faults in the toe verge consistently landward, except near the mouth of the Columbia River where detachment folding of accreted sediment is evident. Furthermore, rocks under the broad midslope terrace west of Washington appear to be intruded by diapirs. The combination of detachment folding, diapirs, and landward-vergent thrust faults all suggest that nearly as far landward as the shelf break, coupling along the interplate decollement is, or has been, low, as suggested by other lines of evidence.

1. Introduction

Great earthquakes have occurred within the Cascadia subduction zone; one such quake apparently rocked this region 300 years ago (e.g. (Heaton and Hartzell, 1987, Bucknam et al., 1992, Clague and Bobrowsky, 1994, Satake et al., 1996)). However because shallow (<30 km) earthquakes are scarce beneath Washington, little is known about potential earthquake source

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PII: S0264–3707(98)00001–5

Table 1
MCS Data

Streamer length	2400 m
Number of channels	48
Group interval	50 m
Shot interval	50 m
Fold	24
Airgun array volume	87.61 (5350 in 3)
Number of guns	16
Processing system	ProMAX™

regions along the interplate decollement. The structure and physical properties of rocks accreted along the continental margin are also poorly known. For these reasons scientists from the U.S. Geological Survey, GEOMAR (Kiel, Germany), and Oregon State University collected multichannel seismic (MCS) reflection data (Table 1) and wide-angle seismic data, using the research vessel *Sonne* (Flueh and Fisher, 1996).

Here we describe MCS data obtained from offshore northern Oregon and southern Washington over a fundamental along-strike transition in the morphology and structure of the late Cenozoic accretionary complex. Although this transition is gradational, we posit that understanding its origin will prove important to estimating the regional earthquake hazard posed by the Cascadia subduction zone.

2. Regional setting

The Cascadia margin of western Oregon and Washington has been a site of plate convergence since the early Eocene. Presently late Miocene crust of the Juan de Fuca plate is being subducted beneath the North American continent at 43 mm/yr along N65°E (Fig. 1; (Engebretson et al., 1985, DeMets et al., 1990)).

The oldest rocks exposed in the forearc of western Washington and northwestern Oregon are Paleocene and Eocene basalt (Fig. 1, Snavely and 1987; and references therein). Around the Olympic Mountains a major thrust fault separates this basalt from underplated, Eocene to middle Miocene, melange and broken formation that forms the mountain core and provides the only exposure of the Cenozoic accretionary complex (Tabor and Cady, 1978, Brandon and Vance, 1992, Orange et al., 1993). Around the Olympic Mountains the complexly deformed accreted rocks are overlain unconformably by less deformed, shallow-marine rocks of late Miocene to late Pliocene age. Pleistocene shallow-water and nonmarine strata blanket older units.

We describe a structural transition, in the accretionary complex, that is evident in regional slope bathymetry. The continental margin south of the Columbia River mouth strikes nearly north, as shown by the 1000 m and 2000 m bathymetric contours Fig. 1. North of this river mouth, however, the margin hinges gradually westward to strike north–northwest and widens considerably, as indicated by the same contours. The widening expresses a midslope terrace. MCS data we describe here were obtained over the transition zone between these margin morphologies.

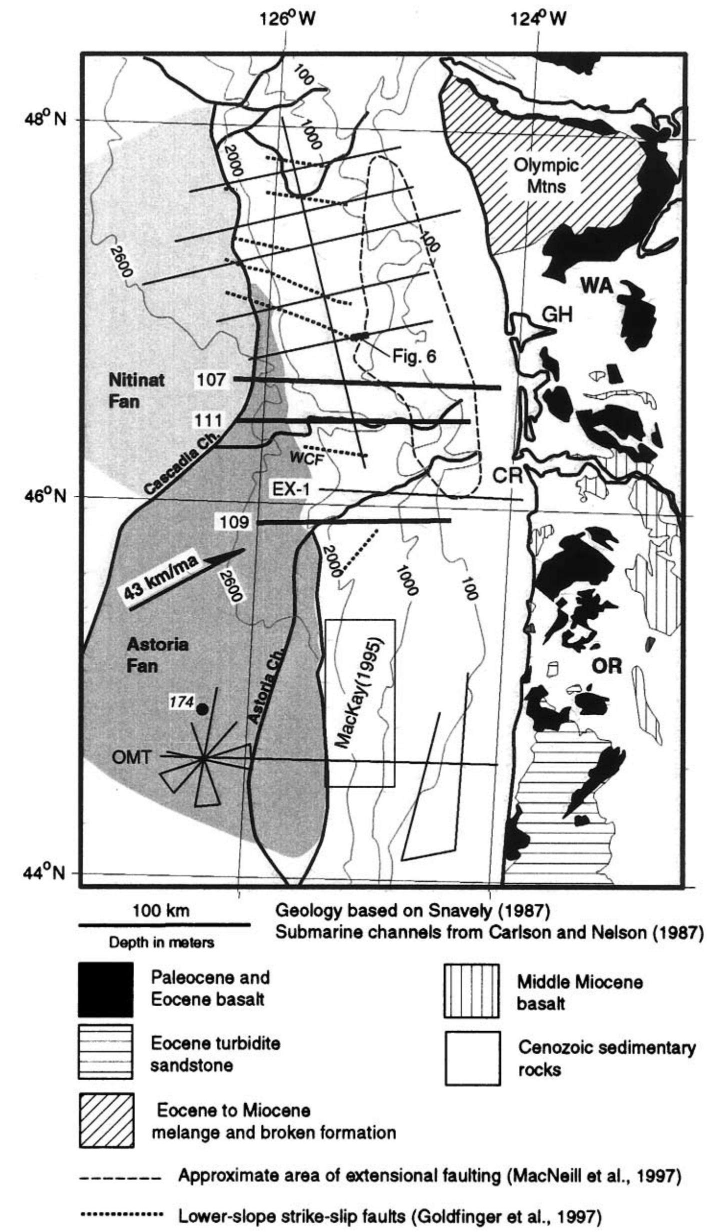

Fig. 1. Tracklines of MCS data collected during the 1996 cruise of the R/V Sonne. CR = Columbia River; GH = Gray's Harbor; OMT = Oregon Margin Transect; OR = Oregon State; WA = Washington State; WCF = Willapa Canyon strike slip fault; 174 = DSDP Site 174.

The continental margin in Cascadia exhibits a complex distribution of compressional, strike–slip and extensional deformation. Within the accretionary wedge under the steep part of the continental margin off Oregon, some major thrust faults verge landward, a fact known since one of the earliest seismic-reflection investigations of accretionary complexes (Seely, 1977). Subsequent studies (Snavely, 1987, Niem et al., 1992, MacKay, 1995) have showed that within the southern third of the area encompassed by the box in Fig. 1 (labeled (MacKay, 1995)) thrust faults verge seaward, whereas under the northern two-thirds of this area most faults verge landward. North of our survey area, west of Vancouver Island, thrust faults in the toe of the accretionary wedge verge seaward (Davis and Hyndman, 1989, Calvert, 1996). Strike slip faults in the oceanic plate have been interpreted to break upward through the upper plate of the subduction zone (Figs. 1, McCaffrey and Goldfinger, 1995, Goldfinger et al. 1997). The configuration of these faults and their estimated strike–slip offsets suggest that the front of the margin is constructed of fault-bounded blocks that rotate clockwise. West of Washington State, listric normal faults under the shelf and upper slope (within the area outlined in Fig. 1) dip mainly seaward and deform rocks as deep as 2 km to 3 km (McNeill et al., 1997). This faulting apparently began during the late Miocene and locally has continued during the Holocene. A structural transition zone, of undetermined kind, has been proposed to extend parallel to the margin front and to separate the inboard, extensional deformation from coeval, outboard accretion.

3. MCS data

Seismic line 109 (Figs 2 and 3) crosses the continental margin south of the Columbia River mouth and crosscuts the Astoria deep sea channel at the toe of the accretionary wedge. On the migrated seismic section, discontinuous reflections from the downgoing oceanic crust were recorded over a distance of about 60 km landward from the deformation front, but a distinct reflection from the interplate decollement cannot be discerned. This seismic section shows a train of five anticlinal ridges. The outer four ridges are regularly spaced about 10 km apart, and the fifth ridge deforms shallow sediment and supports the shelf edge. These folds appear to have formed along thrust faults that verge seaward; fold #4 (Figs 2 and 3) best expresses this vergence. Somewhere south of this seismic line and north of the survey area in (MacKay, 1995) (box in Fig. 1), the vergence direction within the wedge toe changes from landward to seaward.

Deep reflections on the landward flank of the third fold show little evidence for seaward thinning into this flank, but shallow reflections within the flank thin sharply. Furthermore, between the second and third folds a thick section of sediment is concordantly and weakly folded, and only the shallowest strata thin seaward against the second fold's landward flank. These relations suggest that for the deeper and outer folds in accreted rocks, the rate of sediment deposition outstripped the rate of fault and fold deformation.

The Exxon line EX-1 (Niem et al., 1992), just north of line 109 (Fig. 1), shows landward-vergent thrusting within the wedge toe. Shoreward of these frontal thrust faults, the style of deformation appears to be mixed folding and faulting, but structural relief has not developed sufficiently for fold or fault culminations to rise above the seafloor. Indeed sediment directly under the seafloor is little deformed.

Seismic section EX-1 and migrated Sonne section 111 (Figs 2 and 4) reveal similar deformation

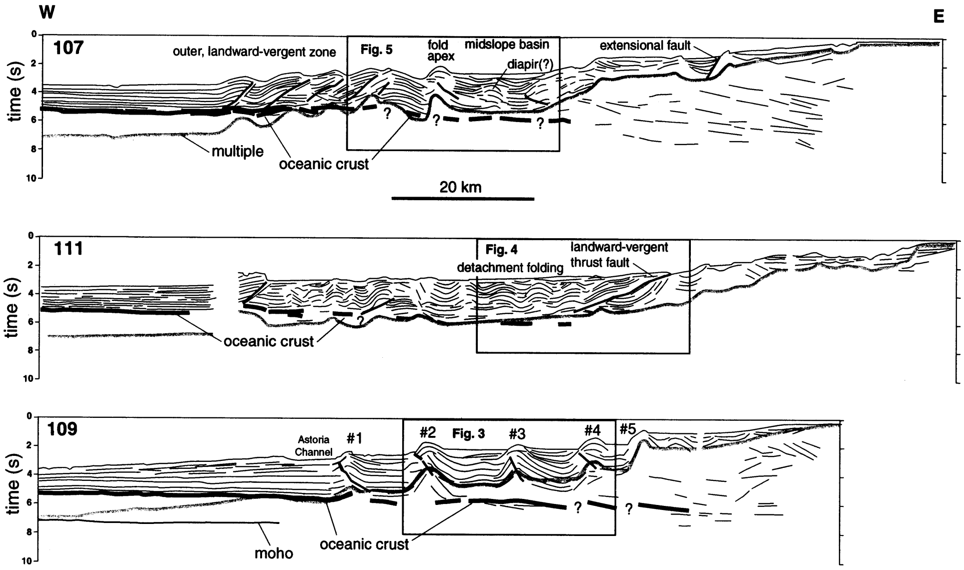

Fig. 2. Line drawings of migrated MCS sections through the Cascadia accretionary complex near the mouth of the Columbia River.

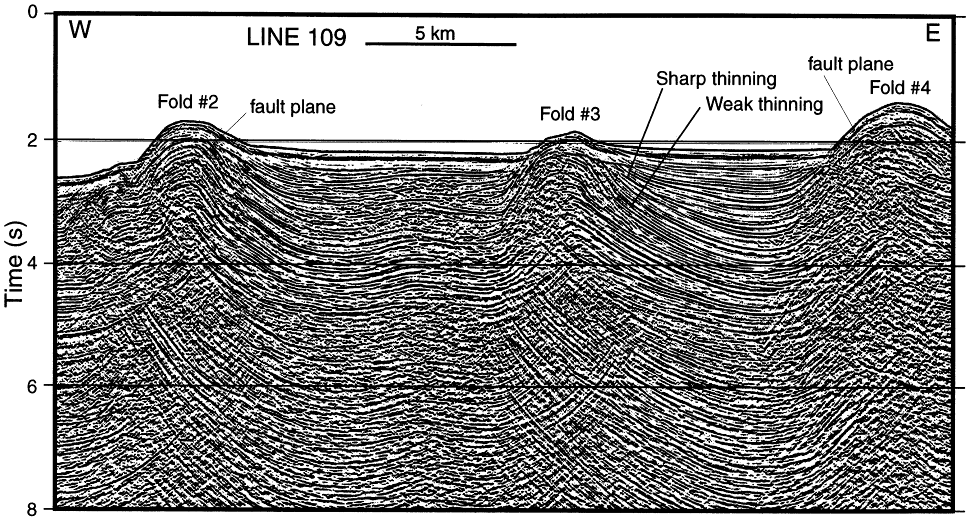

Fig. 3. Detail of migrated seismic section 109, showing the structural transition between landward vergent thrusting under the wedge toe and relatively little deformed strata filling a midslope basin. Location of section shown in Fig. 2.

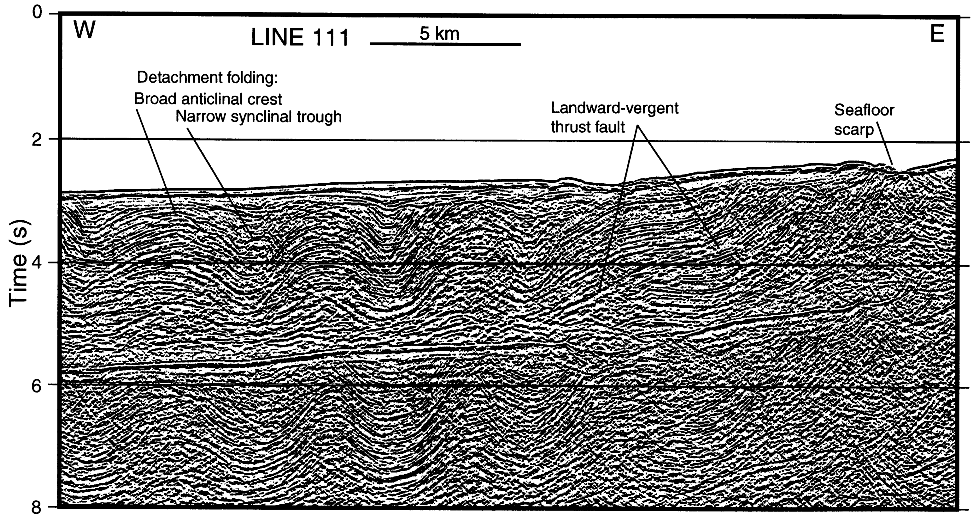

Fig. 4. Detail of migrated seismic section 111, showing detachment folding (broad-crested anticlines and pinched synclines) under the midslope. Location of section shown in Fig. 2.

styles. At the toe of the margin along 111 the landward flank of the first fold is breached by a landward-vergent thrust fault. Strata under the midslope are deformed by mixed folds and faults; even so structural relief there is poorly expressed in seafloor morphology. Particularly under the midslope, the structural style includes broad-crested anticlines that are separated by narrow synclines. This fold geometry is characteristic of detachment folding (e.g. (Dahlstrom, 1990)). Apparently, this type of folding affects strata within a sector of the margin that measures at least 40 km along strike, the distance between lines EX-1 and 111. Section 111 shows that detachment folding ends to the east against a major landward-vergent thrust fault that extends upward to a pronounced seafloor scarp (Figs 2 and 4). The footwall of the thrust fault includes the axis and east limb of a broad syncline that, because of its breadth, contrasts with the pinched synclines west of the fault. Approximately 10 km east of this scarp is the edge of the shelf and upper-slope zone of extensional deformation (McNeill et al., 1997). How the accretionary and extensional domains interleave will be a focus for future research.

The migrated seismic section 107 (Figs 2 and 5) shows five close-spaced thrust faults that deform rocks within the outer 30 km of the wedge toe; all these faults verge landward and extend downward almost to the oceanic crust, meaning that almost all incoming sediment is being frontally accreted. The wedge toe is similarly deformed to the northern limit of our data (Flueh et al., 1997), a distance of about 100 km. Reflections from landward-vergent fault planes are commonly strong, which might result because the faults are fluid conduits, as postulated for similar faults off central Oregon (MacKay, 1995, Cochrane et al., 1996). Along section 107 landward vergence ends abruptly on the east below the sharp apex of an anticline (Figs 2 and 5). Faults within this anticline appear to verge seaward. East of this apex, reflections reveal a 15 km wide, midslope basin that is filled with thick strata that are flat lying except near and within a basin–central zone. From within this zone faults splay upward and outward, and some faults display landward vergence whereas other verge seaward.

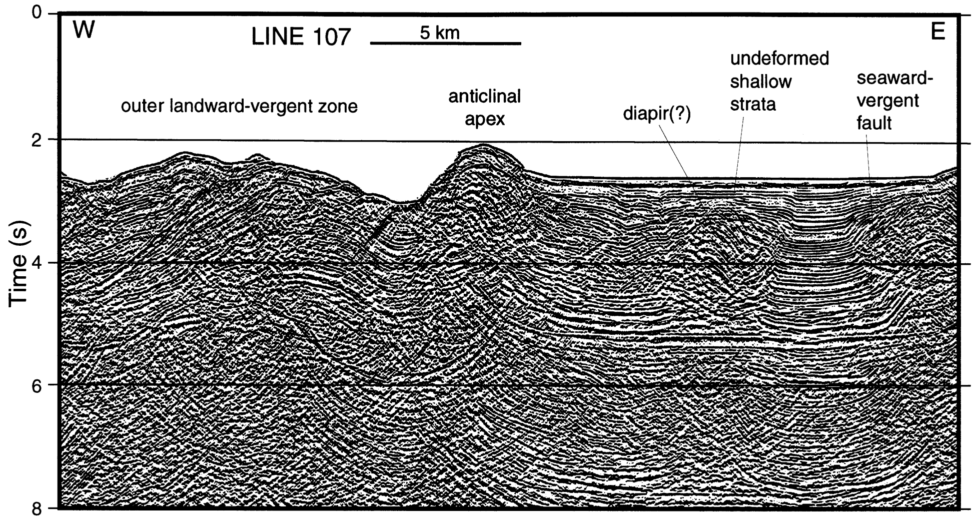

Fig. 5. Detail of migrated seismic section 107, showing regular spacing of isolated anticlines that deform midslope rocks. Location of section shown in Fig. 2.

The flat seafloor over the midslope basin on seismic section 107 extends and broadens northward, becoming the broad midslope terrace west of central Washington.

4. Discussion

Migrated MCS data presented here reveal that west of the Columbia River mouth, folds including detachment folds, are the dominant deformation mode, and they exhibit only scant evidence for a preferred vergence direction. Southward from this river mouth the seafloor dip steepens, and landward vergent structures are succeeded to the south by seaward-vergent ones. Northward from this river mouth the regional seafloor dip decreases as the midslope terrace broadens. The northmost MCS section presented here shows that the predominant deformation mode involves close-spaced, landward-vergent thrust faults, in the outer 30 km of the wedge, that are bordered on the east by a basin containing rocks that are relatively little deformed.

Boundaries between structural subdivisions of the Cascadia margin do not obviously fall along the margin–oblique, strike-slip faults described by (Goldfinger et al., 1997). The Willapa Canyon fault (WCF in Fig. 1) is the main one near seismic lines described here. This fault however crosses the margin between seismic lines EX-1 and 111, yet the sections show substantially the same structural style. If a distinct boundary separates rocks with the different structural styles evident on seismic sections 111 and 107, the boundary must lie north of line 111, where no oblique fault has yet been located. Although the regional structural transition we describe could be related to the oblique faults, we seek alternate causes for this transition.

Together the morphologic and structural transitions suggest an along-strike change in the mechanics of the accretionary complex. Possible causes for this change include: the close-linked

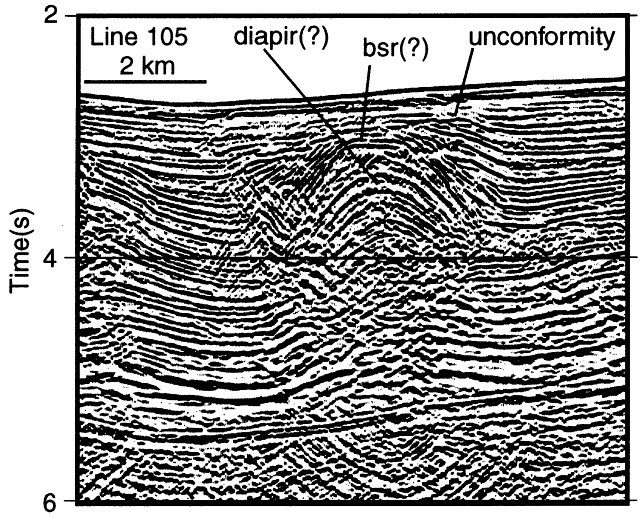

Fig. 6. Migrated seismic image of a probable diapir. Location shown in Fig. 1.

triad of paleoclimate, sediment supply, and fluid pressure; the type of sediment on the subducting plate; the geometry of the underthrust plate; and the degree of interplate coupling.

4.1. Paleoclimate, sediment supply, and fluid pressure

Abruptly increased, late Pleistocene and Holocene sediment influxes from the Columbia and Frasier Rivers caused thick sediment to blanket the continental margin and adjacent abyssal plain. One particular sediment source was catastrophic floods that issued from the Columbia River drainage (O'Connor and Baker, 1992, O'Connor et al., 1995). Rapid deposition could have had profound effect on the accretionary wedge by increasing its internal fluid pressures. In addition, thick sediment newly deposited on the margin and the Nitinat and Astoria fans (Fig. 1) had to be accommodated by the accretionary prism. Increased sedimentation could have affected the wedge critical taper by over steepening the wedge and causing it to collapse. Other sediment was transported to the south end of the midslope terrace via the main drainage, from the ice sheet over Puget Sound, that flowed westward through what is now Grays Harbor (Fig. 1).

Diapirs are classic indicators of overpressured fluids in accretionary complexes and deltas (Brown, 1990, Henry et al., 1996, Lewis and Byrne, 1996, Morley and Guerin, 1996), and diapirs are recognized as important features of the onshore and offshore geology of Cascadia (e.g. (Snavely, 1987, Orange, 1990, Moore et al., 1995)). They apparently began to intrude the margin during the late Miocene. Reflections in the middle of Fig. 6 could be from a diapir, an isolated fold, or a strike slip fault, because the reflective feature is on strike with one of the margin–oblique faults Fig. 1. We cannot distinguish which possibility is the most likely. Similar reflections, however, are evident on section 107 (Figs 2 and 5), and such reflections are common on sections from the north, where the midslope terrace is wide. If the reflective features are diapirs, they suggest fluid-rich rocks in a zone that parallels the trench. (McNeill et al., 1997) postulated a separation zone between the outboard accretionary structures and the inboard extensional deformation. The diapirs(?) may mark the location of such a separator. MCS data shown here reveal that several hundred meters of undeformed sediment overlie the crests of diapirs(?), showing that intrusion has ceased and suggesting that the fluid pressures needed to drive intrusion have dissipated.

Detachment folds, like the broad crested anticlines and pinched synclines evident on seismic section 111, tend to form where shallow, competent units are underlain by thick ductile ones (Wiltschko and Chapple, 1977, Dahlstrom, 1990, Erickson, 1996, Stewart, 1996). Computer modeling of detachment folds indicates that they are favored to develop over faulting where large differences exist in the strength of vertically adjacent rock layers. Fold growth is accompanied by the redistribution of weak, deep strata into anticlinal cores, and if insufficient weak material is present to fill these cores, then fold growth is hampered and shortening is accommodated in some other fashion. From the observed folding on section 111, we surmise that the interplate decollement zone beneath the general area of the Columbia River mouth and Astoria fan is, or was, thick and weak. This agrees with observations that regionally, the degree of interplate coupling is low (e.g. (Hyndman and Wang, 1995, MacKay, 1995, Wang et al., 1995, Goldfinger et al., 1997)).

4.2. Abyssal sediment type

The part of the continental margin west of Washington State lies opposite the Nitinat fan, whereas the part west of Oregon faces the Astoria fan. These fans have disparate sediment sources, suggesting differences in sediment thickness and type as a possible influence on the tectonic style of the margin.

4.3. Plate geometry

The along-strike transition in the accretionary wedge could have been controlled by the downgoing oceanic plate because the plate arches about an east–west axis beneath the Olympic Mountains. The deep plate dips at a lower angle under the mountains than it does below areas to the north and south (Crosson and Owens, 1987, Weaver and Barker, 1988, Brandon and Calderwood, 1990). This change in basement dip may cause the critical taper of the wedge to change along strike.

4.4. Interplate coupling

(Thorson, 1996) proposed that when the continental ice sheet over Puget Sound melted at the end of the Pleistocene, vertical loading across the interplate decollement diminished, and correspondingly, the interplate coupling lessened deep within the subduction zone. Such a rapid change in stress state could have been telegraphed up the dip of the decollement to affect the tectonic regime of the outermost continental margin.

5. Conclusion

The northward transition in margin morphology, from a relatively narrow, steep slope west of Oregon to a broad, midslope terrace off Washington, takes place across a margin sector that is characterized by rapidly changing structural style. Detachment folding near the mouth of the

Columbia River, diapirs, and landward-vergent thrust faults suggest that coupling along the interplate decollement is, or has been, low. Our data provide a snapshot of an accretionary system that is responding to rapid changes in Pleistocene and Holocene climate and deposition rates. The stalled diapirs might mean that fluid pressures are lowering beneath the midslope and that coupling between the plates might be increasing. This would have important consequences for analyzing the earthquake potential of this continental margin.

Acknowledgements

We thank Roland von Huene of GEOMAR and Steven Bohlen of the USGS for funding, support, and guidance. In large part, funding for this cruise was provided by the German Ministry of Education, Research, Science, and Technology (BMBF). Trehu received financial support through external NEHRP grant #1434HQ-96GR02725. We appreciate the untiring support of Captain Papenhagen and his crew aboard the Sonne and the skill and untiring efforts of the technicians at the USGS Marine Facility in Redwood City.

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